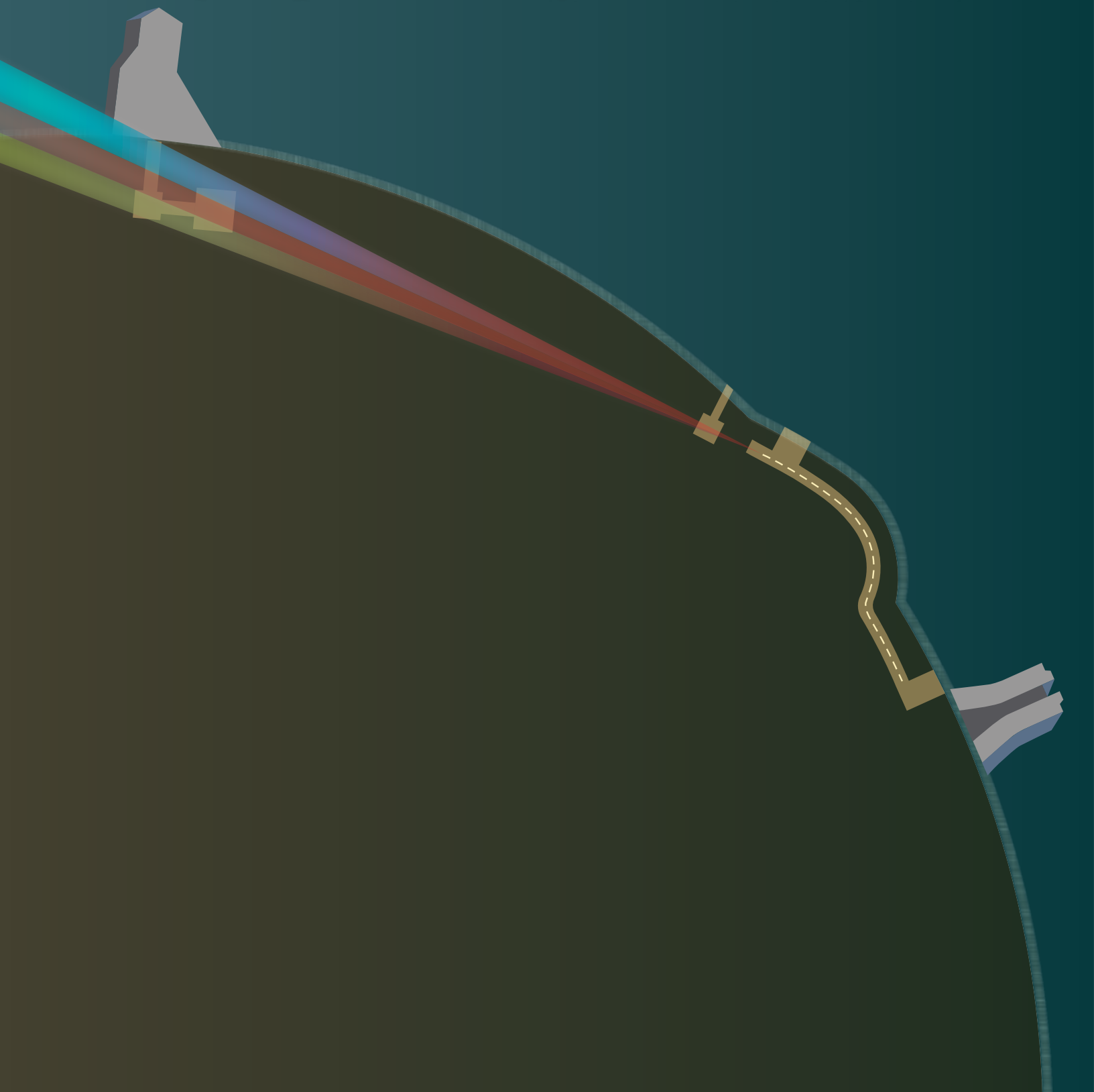
The Long-Baseline Neutrino Experiment

Exploring Fundamental Symmetries of the Universe



Chapter 1 Introduction and Executive Summary

The Long-Baseline Neutrino Experiment (LBNE) will provide a unique, world-leading program for the exploration of key questions at the forefront of particle physics and astrophysics.

Chief among its potential discoveries is that of matter-antimatter symmetry violation in neutrino flavor mixing — a step toward unraveling the mystery of matter generation in the early Universe. Independently, determination of the neutrino mass ordering and precise measurement of neutrino mixing parameters by LBNE may reveal new fundamental symmetries of Nature.

To achieve its ambitious physics objectives as a world-class facility, LBNE has been conceived around three central components:

1. an intense, wide-band neutrino beam
2. a fine-grained *near* neutrino detector just downstream of the neutrino source
3. a massive liquid argon time-projection chamber (LArTPC) deployed as a *far* neutrino detector deep underground, 1,300 km downstream; this distance between the neutrino source and far detector — the *baseline* — is measured along the line of travel through the Earth

The neutrino beam and near detector will be installed at the Fermi National Accelerator Laboratory (Fermilab), in Batavia, Illinois. The far detector will be installed at the Sanford Underground Research Facility in Lead, South Dakota.

The location of its massive high-resolution far detector deep underground will enable LBNE to significantly expand the search for proton decay as predicted by Grand Unified Theories, as well as study the dynamics of core-collapse supernovae through observation of their neutrino bursts, should any occur in our galaxy during LBNE's operating lifetime.

The near neutrino detector will enable high-precision measurements of neutrino oscillations, thereby enhancing the sensitivity to matter-antimatter symmetry violations and will exploit the potential of high-intensity neutrino beams as probes of new physics.

With its extensively developed design and flexible configuration, LBNE provides a blueprint for an experimental program made even more relevant by recent neutrino mixing parameter measurements.

To achieve the transformative physics goals of LBNE in an era of highly constrained funding for basic research in the U.S., the conceptual design has evolved so as to provide a scalable, phased and global approach, while maintaining a U.S. leadership role as the host for a global facility. International partnerships are being actively pursued to both enhance and accelerate the LBNE Project.

LBNE's primary beamline is designed to operate initially with a beam power of 1.2 MW, upgradable to 2.3 MW. This beamline extracts protons with energies from 60 to 120 GeV from the Fermilab Main Injector. The protons collide with a target to generate a secondary beam of charged particles, which in turn decay to generate the neutrino beam.

The liquid argon TPC far detector technology combines fine-grained tracking with total absorption calorimetry. Installed 4,850 ft underground to minimize backgrounds, this detector will be a powerful tool for long-baseline neutrino oscillation physics and underground physics such as proton decay, supernova neutrinos and atmospheric neutrinos. The far detector design is scalable and flexible, allowing for a phased approach, with an initial fiducial mass of at least 10 kt and a final configuration of at least 34 kt.

A high-precision near detector is planned as a separate facility allowing maximal flexibility in phasing and deployment.

The technologies and configuration of the planned LBNE facilities offer excellent sensitivity to a range of physics processes:

- The muon-neutrino (ν_μ) beam produced at Fermilab with a peak flux at 2.5 GeV, coupled to the baseline of 1,300 km, will present near-optimal sensitivity to neutrino/antineutrino charge-parity (CP) symmetry violation effects.
- The long baseline of LBNE will ensure a large matter-induced asymmetry in the oscillations of neutrinos and antineutrinos, thus providing a clear, unambiguous determination of the mass ordering of the neutrino states.
- The near detector located just downstream of the neutrino beamline at Fermilab will enable high-precision long-baseline oscillation measurements as well as precise measurements and searches for new phenomena on its own using the high-intensity neutrino beam.
- The deep-underground LArTPC far detector will provide superior sensitivities to proton decay modes with kaons in the final states, modes that are favored by many Grand Unified and supersymmetric theoretical models.
- Liquid argon as a target material will provide unique sensitivity to the electron-neutrino (ν_e) component of the initial burst of neutrinos from a core-collapse supernova.
- The excellent energy and directional resolution of the LArTPC will allow novel physics studies with atmospheric neutrinos.

The LBNE physics program has been identified as a priority of the global HEP community for the coming decades. The facilities available in the U.S. are the best suited internationally to carry out this program and the substantially developed LBNE design is at the forefront of technical innovations in the field. Timely implementation of LBNE will significantly advance the global HEP program and assure continued intellectual leadership for the U.S. within this community.

Chapter 2 The Science of LBNE

The Standard Model of particle physics describes all of the known fundamental particles and the electroweak and strong forces that, in combination with gravity, govern today's Universe. The observation that neutrinos have mass is one demonstration that the Standard Model is incomplete. By exploring physics beyond the Standard Model, LBNE will address fundamental questions about the Universe:

What is the origin of the matter-antimatter asymmetry in the Universe? Immediately after the Big Bang, matter and antimatter were created equally, yet matter now dominates. By studying the properties of neutrino and antineutrino oscillations, LBNE is pursuing the most promising avenue for understanding this asymmetry.

What are the fundamental underlying symmetries of the Universe? Resolution by LBNE of the detailed mixing patterns and ordering of neutrino mass states, and comparisons to the corresponding phenomena in the quark sector, could reveal underlying symmetries that are as yet unknown.

Is there a Grand Unified Theory of the Universe? Experimental evidence hints that the physical forces observed today were unified into one force at the birth of the Universe. Grand Unified Theories (GUTs), which attempt to describe the unification of forces, predict that protons should decay, a process that has never been observed. LBNE will probe proton lifetimes predicted by a wide range of GUT models.

How do supernovae explode? The heavy elements that are the key components of life — such as carbon — were created in the super-hot cores of collapsing stars. LBNE's design will enable it to detect the neutrino burst from core-collapse supernovae. By measuring the time structure and energy spectrum of a neutrino burst, LBNE will be able to elucidate critical information about the dynamics of this special astrophysical phenomenon.

What more can LBNE discover about the Standard Model? The high intensity of the LBNE neutrino beam will provide a unique probe for precision tests of Standard Model processes as well as searches for new physics in unexplored regions.

Results from the last decade, indicating that the three known types of neutrinos have nonzero mass, mix with one another and oscillate between generations, imply physics beyond the Standard Model [1]. Each of the three flavors of neutrinos, ν_e, ν_μ and ν_τ (Figure 2.1), is known to be a different mix of three mass eigenstates ν_1, ν_2 and ν_3 (Figure 2.2). In the Standard Model, the simple Higgs mechanism, which has now been confirmed by the observation of the Higgs boson [2,3], is responsible for both quark and lepton masses, mixing and charge-parity (CP) violation (the mechanism responsible for matter-antimatter asymmetries). However, the small size of neutrino masses and their relatively large mixing bears little resemblance to quark masses and mixing, suggesting that different physics — and possibly different mass scales — in the two sectors may be present, and motivating precision study of mixing and CP violation in the lepton sector.

The relationship between the three mixing angles θ_{12}, θ_{23}, and θ_{13} and the mixing between the neutrino flavor and mass states can be described as follows [4]:

$$\tan^2\theta_{12} \quad : \quad \frac{\text{amount of } \nu_\mathrm{e} \text{ in } \nu_2}{\text{amount of } \nu_\mathrm{e} \text{ in } \nu_1} \tag{2.1}$$

$$\tan^2\theta_{23} \quad : \quad \text{ratio of } \nu_\mu \text{ to } \nu_\tau \text{ in } \nu_3 \tag{2.2}$$

$$\sin^2\theta_{13} \quad : \quad \text{amount of } \nu_\mathrm{e} \text{ in } \nu_3 \tag{2.3}$$

The frequency of neutrino oscillation among the weak-interaction (flavor) eigenstates depends on the difference in the squares of the neutrino masses, $\Delta m^2_{ij} \equiv m^2_i - m^2_j$; a set of three neutrino mass states implies two independent mass-squared differences (Δm^2_{21} and Δm^2_{32}). The ordering of the mass states is known as the *neutrino mass hierarchy*. An ordering of $m_1 < m_2 < m_3$ is known as the *normal hierarchy* since it matches the ordering of the quarks in the Standard Model, whereas an ordering of $m_3 < m_1 < m_2$ is referred to as the *inverted hierarchy*.

Since each flavor eigenstate is a mixture of three mass eigenstates, there can be an overall phase difference between the quantum states, referred to as δ_CP. A nonzero value of this phase implies that neutrinos and antineutrinos oscillate differently — a phenomenon known as charge-parity (CP) violation. δ_CP is therefore often referred to as the *CP phase* or the *CP-violating phase*.

Recent theoretical advances have demonstrated that CP violation, necessary for the generation of the Baryon Asymmetry of the Universe at the GUT scale (baryogenesis), can be directly related to the low-energy CP violation in the lepton sector that could manifest in neutrino oscillations. As an example, the theoretical model described in [5] predicts that leptogenesis, the generation of the analogous lepton asymmetry, can be achieved if

$$|\sin\theta_{13}\sin\delta_{\rm CP}| \gtrsim 0.11 \tag{2.4}$$

This implies $|\sin\delta_{\rm CP}| \gtrsim 0.7$ given the latest global fit value of $|\sin\theta_{13}|$ [6].

The significant impact of the matter effect on the $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillation probabilities at longer baselines (Figures 2.3 and 2.4) implies that ν_e appearance measurements over long distances through the Earth provide a powerful probe into the neutrino mass hierarchy question: is $m_1 > m_3$ or vice-versa?

Studying ν_μ disappearance probes $\sin^2 2\theta_{23}$ and $|\Delta m^2_{32}|$ with very high precision. Disappearance measurements can therefore determine whether ν_μ-ν_τ mixing is maximal or near maximal such that $\sin^2 2\theta_{23} = 1$, but they cannot resolve the octant of θ_{23} if ν_μ-ν_τ mixing is less than maximal. Combining the ν_μ disappearance signal with the ν_e appearance signal can help determine the θ_{23} octant and constrain some of the theoretical models of quark-lepton universality.

Searches for proton decay, bound-neutron decay and similar processes such as di-nucleon decay and neutron-antineutron oscillations test the apparent but unexplained conservation law of baryon number. These decays are already known to be rare based on decades of prior searches, all of which have produced negative results. If measurable event rates or even a single-candidate event were to be found, it would be sensible to presume that they occurred via unknown virtual processes based on physics beyond the Standard Model. The impact of demonstrating the existence of a baryon-number-violating process would be profound.

The observation of even a single unambiguous proton decay event would corroborate the idea of unification and the signature of the decay would give strong guidance as to the nature of the underlying theory.

The expected rate of core-collapse supernovae is two to three per century in the Milky Way [7,8]. In a 20-year experimental run, LBNE's probability of observing neutrinos from a core-collapse supernova in the Milky Way is about 40%. The detection of thousands of supernova-burst neutrinos from this event would dramatically expand the science reach of the experiment, allowing observation of the development of the explosion in the star's core and probing the equation-of-state of matter at nuclear densities. In addition, independent measurements of the neutrino mass hierarchy and the θ_{13} mixing angle are possible, as well as additional constraints on physics beyond the Standard Model.

Each of the topics that can be addressed by studying supernova-burst neutrinos represent important outstanding problems in modern physics, each worthy of a separate, dedicated experiment, and the neutrino physics and astrophysics communities would receive payback simultaneously. The opportunity of targeting these topics in a single experiment is very attractive, especially since it may come only at incremental cost to the LBNE Project.

Chapter 3 Project and Design

The LBNE Project was formed to design and construct the Long-Baseline Neutrino Experiment. The experiment will comprise a new, high-intensity neutrino source generated from a megawatt-class proton accelerator at Fermi National Accelerator Laboratory (Fermilab) directed at a large far detector at the Sanford Underground Research Facility in Lead, SD. A near detector will be located about 500 m downstream of the neutrino production target. LBNE is currently planned as a phased program, with increased scientific capabilities at each phase.

- The experimental facilities are designed to meet the primary scientific objectives of the experiment: (1) fully characterize neutrino oscillations, including measuring the value of the unknown CP-violating phase, δ_{CP}, and determining the ordering of the neutrino mass states, (2) significantly improve proton decay lifetime limits, and (3) measure the neutrino flux from potential core-collapse supernovae in our galaxy.
- The LBNE beamline, based on the existing *Neutrinos at the Main Injector* (NuMI) beamline design, is designed to deliver a wide-band, high-purity ν_μ beam with a peak flux at 2.5 GeV, which optimizes the oscillation physics potential at the 1,300-km baseline. The beamline will operate initially at 1.2 MW and will be upgradable to 2.3 MW utilizing a proton beam with energy tunable from 60 to 120 GeV.
- The full-scope LBNE far detector is a liquid argon time-projection chamber (LArTPC) of fiducial mass 34 kt.

  The TPC design is modular, allowing flexibility in the choice of initial detector size.
- The LBNE far detector will be located 4,850 feet underground, a depth favorable for LBNE's search for proton decay and detection of the neutrino flux from a core-collapse supernova.
- The high-precision near detector and its conventional facilities can be built as an independent project, at the same time as the far detector and beamline, or later.

The 1,300-km baseline has been determined to provide optimal sensitivity to CP violation and the measurement of δ_{CP}, and is long enough to enable an unambiguous determination of the neutrino mass hierarchy [9].

Fermilab, located 40 miles west of Chicago, Illinois, is a DOE-funded laboratory dedicated to high energy physics. The laboratory builds and operates accelerators, detectors and other facilities that physicists from all over the world use to carry out forefront research.

Dramatic discoveries in high energy physics have revolutionized our understanding of the interactions of the particles and forces that determine the nature of matter in the Universe. Two major components of the Standard Model of Fundamental Particles and Forces were discovered at Fermilab: the bottom quark (May-June 1977) and the top quark (February 1995). In July 2000, Fermilab experimenters announced the first direct observation of the tau neutrino, thus filling the final slot in the lepton sector of the Standard Model. Run II of the Fermilab Tevatron Collider was inaugurated in March 2001. The Tevatron was the world's highest-energy particle accelerator and collider until the Large Hadron Collider at CERN came online in 2011.

While CERN now hosts the world's highest-energy particle collider, the Fermilab accelerator complex is being retooled to produce the world's highest-intensity beams of protons, muons and neutrinos. Scientists from around the world can exploit this capability to pursue cutting-edge research in the lepton sector of the Standard Model where strong hints of new physics have surfaced.

The beamline and near detector for LBNE will be constructed at Fermilab, referred to as the *Near Site*.

The Sanford Underground Research Facility [10] is a laboratory located on the site of the former Homestake gold mine in Lead, SD that is dedicated to underground science. This laboratory has been selected as the location of the far detector for LBNE, and is referred to as the *Far Site*.

Underground neutrino experiments in the former mine date back to 1967 when nuclear chemist Ray Davis installed a solar neutrino experiment 4,850 feet below the surface [11]. Ray Davis earned a share of the Nobel Prize for physics in 2002 for his experiment, which ran until 1993.

LBNE is envisioned as the next-generation, multi-decade neutrino experiment at this site seeking groundbreaking discoveries.

The LBNE neutrino beamline, located at Fermilab, utilizes a conventional horn-focused neutrino beam produced from pion decay-in-flight, based largely on the highly successful NuMI beamline design:

- The primary beam utilizes 60- to 120-GeV protons from the Main Injector accelerator. The primary beamline is embedded in an engineered earthen embankment — a novel construction concept to reduce costs and improve radiological controls.
- The beamline is designed to operate at 1.2 MW and to support an upgrade to 2.3-MW operation.
- The beamline will generate a wide-band, high-purity beam, selectable for muon neutrinos or muon antineutrinos. Its tunable energies from 60 to 120 GeV will be well matched to the 1,300-km neutrino oscillation baseline.

A high-resolution near neutrino detector located approximately 500 m downstream of the LBNE neutrino production target, as shown in Figure **??**, is a key component of the full LBNE scientific program:

- The near neutrino detector will enable the LBNE experiment to achieve its primary scientific goals — in particular discovery-level sensitivity to CP violation and high-precision measurements of the neutrino oscillation parameters, including the unknown CP-violating phase, δ_{CP}.
- A rich program of LBNE physics measurements at the near detector will exploit the potential of high-intensity neutrino beams as probes of new physics.

The full-scope LBNE far detector is a liquid argon time-projection chamber of fiducial mass 34 kt located at the 4,850-ft level of the Sanford Underground Research Facility. The LArTPC technology allows for high-precision identification of neutrino flavors, offers excellent sensitivity to proton decay modes with kaons in the final state and provides unique sensitivity to electron neutrinos from a core-collapse supernova. The full detector size and its location at a depth of 4,850 feet will enable LBNE to meet the primary scientific goals — in particular, to find evidence for CP violation over a large range of δ_{CP} values, and to significantly advance proton-decay lifetime limits. Conceptual designs of the 34-kt underground detector are well developed.

- The far detector for the initial phase of LBNE will have fiducial mass of *at least* 10 kt. This mass allows for high probability determination of the neutrino mass hierarchy and can provide evidence for CP violation, if this effect is large.
- The detector needs to be located deep underground to provide sensitivity for proton decay searches in the kaon modes and for measuring neutrinos from potential supernovae in the galaxy.
- A conceptual design for a 10-kt LArTPC has been developed, thoroughly reviewed and found to be sound.
- LBNE is working with international partners in an effort to deploy a more massive far detector in the initial phase.

Chapter 4 Neutrino Mixing, Mass Hierarchy and CP Violation

LBNE is designed to address the science of neutrino oscillations with superior sensitivity to many mixing parameters in a single experiment, in particular,

1. precision measurements of the parameters that govern $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations; this includes precision measurement of the third mixing angle θ_{13}, measurement of the CP-violating phase $\delta_{\rm CP}$, and determination of the mass ordering (the sign of Δm^2_{32})
2. precision measurements of $\sin^2 2\theta_{23}$ and $|\Delta m^2_{32}|$ in the $\nu_\mu/\overline{\nu}_\mu$ disappearance channel
3. determination of the θ_{23} octant using combined precision measurements of the $\nu_e/\overline{\nu}_e$ appearance and $\nu_\mu/\overline{\nu}_\mu$ disappearance channels
4. search for nonstandard physics that can manifest itself as differences in higher-precision measurements of ν_μ and $\overline{\nu}_\mu$ oscillations over long baselines

LBNE will be definitive in its ability to discriminate between normal and inverted mass hierarchy for the allowed range of unknown parameters such as $\delta_{\rm CP}$ and $\sin^2\theta_{23}$. To assess the sensitivity of LBNE to this physics, particularly for the case of less favorable parameter values, detailed understanding of statistical significance is essential.

At the true values of $\delta_{\rm CP}$ for which the mass hierarchy asymmetry is maximally offset by the leptonic CP asymmetry, LBNE's sensitivity to the mass hierarchy is at its minimum. Even in this case, with a 34-kt LArTPC operating for six years in a 1.2-MW beam, the $|\Delta\chi^2|$ value obtained in a typical data set will exceed 25, allowing LBNE on its own to rule out the incorrect mass ordering at a confidence level above $1-3.7\times10^{-6}$. Considering fluctuations, LBNE will measure, in $\geq 97.5\%$ of all possible data sets for this least favorable scenario, a value of $|\Delta\chi^2|$ equal to 9 or higher, which corresponds to a $\geq 99\%$ probability of ruling out the incorrect hierarchy hypothesis.

Assuming the normal hierarchy, the most recent global fit of experimental data for the three-neutrino paradigm favors a value of $\delta_{\rm CP}$ close to $-\pi/2$ with $\sin\delta_{\rm CP} < 0$ at a confidence level of $\sim 90\%$ [6] (Figure 4.15). LBNE alone with a 10-kt detector and six years of running would resolve with $\geq 3\sigma$ precision the question of whether CP is violated for the currently favored value of $\delta_{\rm CP}$. With a 34-kt detector running for six years, LBNE, alone will achieve a precision approaching 6σ.

With sufficient exposure, LBNE can resolve the θ_{23} octant with $> 3\sigma$ significance even if θ_{23} is within a few degrees of $45°$, the value at which the mixing between the ν_μ and ν_τ neutrino states is maximal.

Atmospheric neutrinos are unique among sources used to study oscillations: the flux contains neutrinos and antineutrinos of all flavors, matter effects play a significant role, both Δm^2 values contribute, and the oscillation phenomenology occurs over several orders of magnitude each in energy (Figure 2.8) and path length. These characteristics make atmospheric neutrinos ideal for the study of oscillations (in principle sensitive to all of the remaining unmeasured quantities in the PMNS matrix) and provide a laboratory in which to search for exotic phenomena for which the dependence of the flavor-transition and survival probabilities on energy and path length can be defined. The large LBNE LArTPC far detector, placed at sufficient depth to shield against cosmic-ray background, provides a unique opportunity to study atmospheric neutrino interactions with excellent energy and path-length resolutions.

In the region of $\delta_{\rm CP}$ where the LBNE neutrino-beam-only analysis is least sensitive to the mass hierarchy, atmospheric neutrinos measured in the same experiment offer comparable sensitivity. The combined beam and atmospheric neutrino sensitivity to the mass hierarchy is $|\sqrt{\Delta\chi^2}| > 6$ for all values of $\delta_{\rm CP}$ ($\sin^2\theta_{23} = 0.4$) in a 34-kt detector, assuming a 1.2-MW beam running for ten years. It is important to note that the combined sensitivity is better than the sum of the separate $\Delta\chi^2$ values, as the atmospheric data help to remove degeneracies in the beam data.

Due to the very small masses and large mixing of neutrinos, their oscillations over a long distance act as an exquisitely precise interferometer with high sensitivity to very small perturbations caused by new physics phenomena, such as:

- nonstandard interactions in matter that manifest in long-baseline oscillations as deviations from the three-flavor mixing model
- new long-distance potentials arising from discrete symmetries that manifest as small perturbations on neutrino and antineutrino oscillations over a long baseline
- sterile neutrino states that mix with the three known active neutrino states
- large compactified extra dimensions from String Theory models that manifest through mixing between the Kaluza-Klein states and the three active neutrino states

Full exploitation of LBNE's sensitivity to such new phenomena will require higher-precision predictions of the unoscillated neutrino flux at the far detector and large exposures.

With tight control of systematics, LBNE will reach 5σ sensitivity to CP violation for a large fraction of δ_{CP} values. LBNE delivers the best resolution of the value of δ_{CP} with the lowest combination of power-on-target and far detector mass when compared to other future proposed neutrino oscillation experiments (Figure 4.33).

Chapter 5 Nucleon Decay Motivated by Grand Unified Theories

Baryon number conservation is an unexplained symmetry in the Universe with deep connections to both cosmology and particle physics. As one of the conditions underlying the observed matter-antimatter asymmetry of the Universe, baryon number *should* be violated. Nucleon decay, which is a manifestation of baryon number violation, is a hallmark of many Grand Unified Theories (GUTs), theories that connect quarks and leptons in ways not envisioned by the Standard Model. Observation of proton or bound-neutron decay would provide a clear experimental signature of baryon number violation.

Predicted rates for nucleon decay based on GUTs are uncertain but cover a range directly accessible with the next generation of large underground detectors. LBNE, configured with its massive, deep-underground LArTPC far detector, offers unique opportunities for the discovery of nucleon decay, with sensitivity to key decay channels an order of magnitude beyond that of the current generation of experiments.

The LBNE LArTPC's superior detection efficiencies for decay modes that produce kaons will outweigh its relatively low mass compared with multi-hundred-kiloton water Cherenkov detectors. Because the LArTPC can reconstruct protons that are below Cherenkov threshold, it can reject many atmospheric-neutrino background topologies by vetoing on the presence of a recoil proton. Due to its excellent spatial resolution, it also performs better for event topologies with displaced vertices, such as $p \to K^+\overline{\nu}$ (for multi-particle K^+ decay topologies) and $p \to K^0\mu^+$. The latter mode is preferred in some SUSY GUTs.

Figure 5.4 demonstrates that to improve the current limits on the $p \to \overline{\nu}K^+$, set by Super–Kamiokande, significantly beyond that experiment's sensitivity, a LArTPC detector of at least 10 kt, installed deep underground, is needed. A 34-kt detector will improve the current limits by an order of magnitude after running for two decades. Clearly a larger detector mass would improve the limits even more in that span of time.

Chapter 6 Core-Collapse Supernova Neutrinos

Neutrinos emitted in the first few seconds of a core-collapse supernova carry with them the potential for great insight into the mechanisms behind some of the most spectacular events that have played key roles in the evolution of the Universe. Collection and analysis of this high-statistics neutrino signal from a supernova within our galaxy would provide a rare opportunity to witness the energy and flavor development of the burst as a function of time. This would in turn shed light on the astrophysics of the collapse as well as on neutrino properties.

A number of astrophysical phenomena associated with supernovae are expected to be observable in the supernova-neutrino signal, providing a remarkable window into the event, for example:

- The initial burst, primarily composed of ν_e and called the *neutronization* or *breakout* burst, represents only a small component of the total signal. However, oscillation effects can manifest in an observable manner in this burst, and flavor transformations can be modified by the *halo* of neutrinos generated in the supernova envelope by scattering [12].
- The formation of a black hole would cause a sharp signal cutoff (e.g., [13,14]).
- Shock wave effects (e.g., [15]) would cause a time-dependent change in flavor and spectral composition as the shock wave propagates.
- The standing accretion shock instability (SASI) [16,17], a *sloshing* mode predicted by 3D neutrino-hydrodynamics simulations of supernova cores, would give an oscillatory flavor-dependent modulation of the flux.
- Turbulence effects [18,19] would also cause flavor-dependent spectral modification as a function of time.

LBNE, with its high-resolution LArTPC far detector, is uniquely sensitive to the ν_e component of the neutrino flux from a core-collapse supernova within our galaxy. The ν_e component of the neutrino flux dominates the initial neutronization burst of the supernova. Preliminary studies indicate that such a supernova at a distance of 10 kpc would produce $\sim$3,000 events in a 34-kt LArTPC. The time dependence of the signal will allow differentiation between different neutrino-driven core-collapse dynamical models, and will exhibit a discernible dependence on the neutrino mass hierarchy.

A low energy threshold of ~ 5 MeV will enable the detector to extract the rich information available from the ν_e supernova flux. LBNE's photon detection system is being designed to provide a high-efficiency trigger for supernova events. Careful design and quality control of the detector materials will minimize low-energy background from radiological contaminants.

Chapter 7 Precision Measurements with a High-Intensity Neutrino Beam

The LBNE near neutrino detector provides scientific value beyond its essential role of calibrating beam and neutrino interaction properties for the long-baseline physics program described in Chapter 4. By virtue of the theoretically clean, purely weak leptonic processes involved, neutrino beams have historically served as unique probes for new physics in their interactions with matter. The high intensity and broad energy range of the LBNE beam will open the door for a highly capable near detector to perform its own diverse program of incisive investigations.

Neutrinos and antineutrinos are the most effective probes for investigating electroweak physics. Interest in a precise determination of the weak mixing angle ($\sin^2\theta_W$) at LBNE energies via neutrino scattering is twofold: (1) it provides a direct measurement of neutrino couplings to the Z boson and (2) it probes a different scale of momentum transfer than LEP did by virtue of not being at the Z boson mass peak.

The strange-quark content of the proton and its contribution to the proton spin remain enigmatic [20]. The question is whether the strange quarks contribute substantially to the vector and axial-vector currents of the nucleon. A large observed value of the strange-quark contribution to the nucleon spin (axial current), Δs, would enhance our understanding of the proton structure.

The spin structure of the nucleon also affects the couplings of axions and supersymmetric particles to dark matter.

Precision measurements of (anti)neutrino differential cross sections in the LBNE near detector will provide additional constraints on several key nucleon structure functions that are complementary to results from electron scattering experiments.

In addition, these measurements would directly improve LBNE's oscillation measurements by providing accurate simulation of neutrino interactions in the far detector and offer an estimate of all background processes that are dependent upon the angular distribution of the outgoing particles in the far detector. Furthermore, certain QCD analyses — i.e., global fits used for extraction of parton distribution functions (PDFs) via the differential cross sections measured in ND data — would constrain the systematic error in precision electroweak measurements. This would apply not only in neutrino physics but also in hadron collider measurements.

One of the most compelling physics topics accessible to LBNE's high-resolution near detector is the isospin physics using neutrino and antineutrino interactions. This physics involves the Adler sum rule and tests isospin (charge) symmetry in nucleons and nuclei.

The most economical way to handle the problems of neutrino masses, dark matter and the Baryon Asymmetry of the Universe in a unified way may be to add to the Standard Model (SM) three Majorana singlet fermions with masses roughly on the order of the masses of known quarks and leptons using the seesaw mechanism [21]. The appealing feature of this theory (called the νMSM for *Neutrino Minimal SM*) [22] is that every left-handed fermion has a right-handed counterpart, leading to a consistent way of treating quarks and leptons.

The most efficient mechanism proposed for producing these heavy sterile singlet states experimentally is through weak decays of heavy mesons and baryons, as can be seen from the left-hand diagram in Figure 7.4, showing some examples of relevant two- and three-body decays [23]. These heavy mesons can be produced by energetic protons scattering off the LBNE neutrino production target and the heavy singlet neutrinos from their decays detected in the near detector.

Given a roughly 500-m baseline and a low-energy beam, the LBNE ND can reach the same value $L/E_\nu \sim 1$ as MiniBooNE and LSND. The large fluxes and the availability of fine-grained detectors make the LBNE program well suited to search for active-sterile neutrino oscillations beyond the three-flavor model with Δm^2 at the eV^2 scale.

Recently, a great deal of interest has been paid to the possibility of studying models of light (sub-GeV) Dark Matter at low-energy, fixed-target experiments [24,25,26,27]. High-flux neutrino beam experiments — such as LBNE — have been shown to potentially provide coverage of DM+mediator parameter space that cannot be covered by either direct detection or collider experiments.

Chapter 8 Additional Far Detector Physics Opportunities

The deep underground location of LBNE's LArTPC far detector will expand the range of science opportunities it can pursue to potentially include observation of solar and other low-energy neutrinos, dark matter, magnetic monopoles and nucleon-antinucleon transitions.

Detection of solar and other low-energy neutrinos is challenging in a LArTPC because of high intrinsic detection energy thresholds for the charged-current (CC) interaction on argon ($>$5 MeV). To be competitive, this physics requires either a very low visible-energy threshold ($\sim$1 MeV) or a very large mass (50 kt). However, compared with other technologies, a LArTPC offers a large cross section and unique signatures from de-excitation photons. Aggressive R&D efforts in low-energy triggering and control of background from radioactive elements may make detection in LBNE possible, and a large detector mass would make the pursuit of these measurements worthwhile.

The LBNE far detector's large mass and directional tracking capabilities will enable it to act as a *neutrino telescope* and search for neutrino signals produced by annihilations of dark matter particles in the Sun and/or the core of the Earth. Detection of high-energy neutrinos coming exclusively from the Sun's direction, for example, would provide clear evidence of dark matter annihilation [28].

A liquid argon detector such as LBNE's far detector is sensitive to the ν_e component of the diffuse relic supernova-neutrino flux, whereas water Cherenkov and scintillator detectors are sensitive to the $\overline{\nu}_e$ component. However, backgrounds in liquid argon are as yet unknown, and a huge exposure ($>$500 kt $\cdot$ years) would likely be required for observation. Given a detector of the scale required to achieve these exposures (50 kt to 100 kt) together with tight control of backgrounds, LBNE — in the long term — could play a unique and complementary role in the physics of relic neutrinos.

Chapter 9 Summary and Conclusion

With DOE CD-1 ("Alternate Selection and Cost Range") approval in hand, the LBNE Project is working toward its technical design specifications, including detailed costs and schedule, in preparation for CD-2 ("Performance Baseline"). It should be noted that the Project already has fully developed schedules for both the CD-1 scope (10-kt far detector on the surface at the Sanford Underground Research Facility, no near neutrino detector), and for the full-scope (34-kt far detector located deep underground and near neutrino detector) for the scenario of funding solely from DOE. Partnerships with non-DOE groups are being sought to enable the construction of LBNE with a near neutrino detector and an underground far detector mass greater than 10 kt in the first phase.

Using the current understanding of DOE funding profiles, we outline one plausible long-term timeline that integrates evolution of LBNE detector mass with development of the Fermilab accelerator complex (i.e., PIP-II) and contributions from non-DOE partners. Implicit in this timeline is an assumption that agreements with new partners be put in place on a timescale of three years (by 2017). In this scenario, the milestones that bear on the physics are as follows:

1. LBNE begins operation in 2025 with a 1.2-MW beam and a 15-kt far detector. (In such a scenario, a significant fraction of the far detector mass might be provided in the form of a standalone LArTPC module developed, funded, and constructed by international partners.)
2. Data are recorded for five years, for a net exposure of 90 kt · MW · year.
3. In 2030, the LBNE far detector mass is increased to 34 kt, and proton beam power is increased to 2.3 MW.
4. By 2035, after five years of additional running, a net exposure of 490 kt · MW · year is attained.

The measurement of the neutrino mass hierarchy and search for CP violation in LBNE will further clarify the pattern of mixing and mass ordering in the lepton sector and its relation to the patterns in the quark sector. The impact of exposures of $90\,\mathrm{kt} \cdot \mathrm{MW} \cdot \mathrm{year}$ (2030) and $490\,\mathrm{kt} \cdot \mathrm{MW} \cdot \mathrm{year}$ (2035) for Mass Hierarchy and CP-violation signatures is easily extracted from Figure 4.16. Should CP be violated through neutrino mixing effects, the typical signal in LBNE establishing this would have a significance of at least three (2030) and five standard deviations (2035), respectively for 50% of δ_{CP} values (and greater than three standard deviations for nearly 75% of δ_{CP} by 2035). In such a scenario, the mass hierarchy can be resolved with a sensitivity for a typical experiment of $\sqrt{\overline{\Delta\chi^2}} \geq 6$ for 50% (100%) of δ_{CP} by 2030 (2035).

LBNE represents a world-class U.S.-based effort to address the science of neutrinos with technologically advanced experimental techniques. By anchoring the U.S. Intensity Frontier program [29], LBNE provides a platform around which to grow and sustain core infrastructure for the community. Development of the Fermilab accelerator systems, in particular, will not only advance progress toward achieving the science goals of LBNE, it will also greatly expand the capability of Fermilab to host other key experimental programs at the Intensity Frontier.

Understanding the fundamental nature of fermion flavor, the existence of CP violation in the lepton sector and how this relates to the Baryon Asymmetry of the Universe; knowing whether proton decay occurs and how; and elucidating the dynamics of supernova explosions all stand among the grand scientific questions of our times. The bold approach adopted for LBNE provides the most rapid and cost-effective means of addressing these questions. With the support of the global HEP community, the vision articulated in this document can be realized in a way that maintains the level of excitement for particle physics and the inspirational impact it has in the U.S. and worldwide.

Appendix A LBNE Detector Simulation and Reconstruction

Appendix B Neutrino-Nucleon Scattering Kinematics

Acknowledgments

This report is the result of an initial collaboration-wide effort to prepare a whitepaper for the APS Division of Particles and Fields Community Summer Study 2013 [30]. The paper has evolved into LBNE's formal science document due to the hard work of many LBNE Collaboration and Project members. We thank those colleagues who made significant contributions and provided excellent feedback on drafts of this document. The following is a nonexhaustive list of LBNE collaborators who made major contributions to this document. A major contribution is defined as $\geq$ a section and/or a study reported in a figure prepared for this document.

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Appendix B	Mary Bishai*, Roberto Petti

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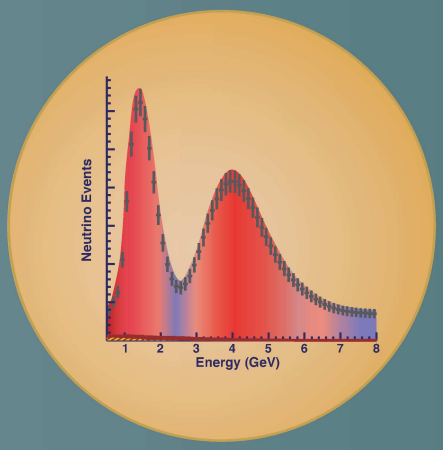
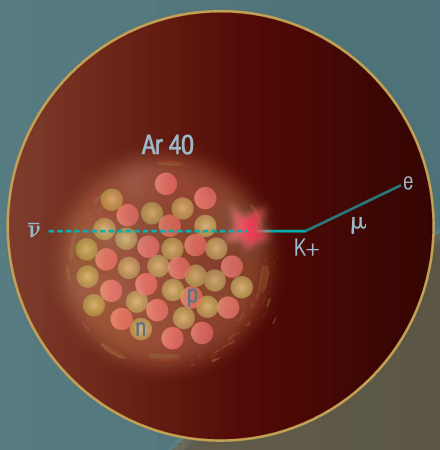
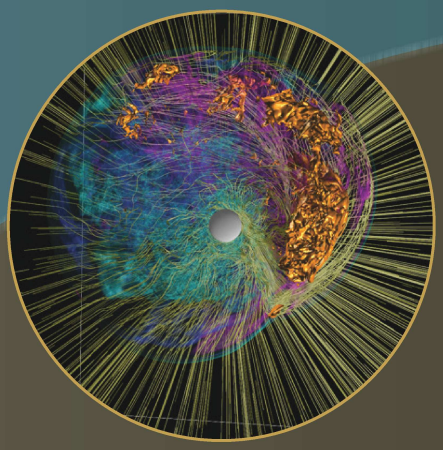


Through precise studies of neutrino flavor oscillations enabled by an intense, optimized beam and advanced detectors, LBNE aims to shed light on the mystery of the matter-antimatter asymmetry in the Universe.



With the world's largest cryogenic particle detector deep underground, LBNE will probe the stability of matter and its relation to the Grand Unification of forces.



LBNE's observation of thousands of neutrinos from a core-collapse supernova in the Milky Way would allow us to peer inside a newly-formed neutron star and potentially witness the birth of a black hole.

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